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This is the first of four quarterly technical reports submitted under ARO contract number DAAG55-97-C-0029. This Phase II SBIR concerns the development of an advanced adaptive CFD capability for predicting the phenomenon of dynamic stall. The new CFD capability is based on the concept of Unstructured MacroCells (UMC). The present report is a description of the work accomplished during the period of April 1, 1997, to July 2, 1997.

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ADVANCED ADAPTIVE CFD METHODOLOGY FOR DYNAMIC STALL

TECHNICAL REPORT

PATRICK H. REISENTHEL

JULY 1997

U.S. ARMY RESEARCH OFFICE

CONTRACT DAAG55-97-C-0029

NIELSEN ENGINEERING & RESEARCH, INC.
526 CLYDE AVENUE · MOUNTAIN VIEW, CALIFORNIA

FOREWORD

This is the first of four quarterly technical reports submitted under ARO contract number DAAG55-97-C-0029. This Phase II SBIR concerns the development of an advanced adaptive CFD capability for predicting the phenomenon of dynamic stall. The new CFD capability is based on the concept of Unstructured MacroCells (UMC) [1]. The present report is a description of the work accomplished during the period of April 1, 1997, to July 2, 1997. This description is preceded by a brief summary of the rationale for an improved prediction methodology and the Phase II objectives. As of 6/28/97, 4.6% of the contract costs have been expended.

PROBLEM DEFINITION AND OBJECTIVES

Evidence that the genesis of the dynamic stall phenomenon is the early formation of an extremely thin vorticity spike within the leading edge boundary layer [2] has driven the needs of computational methods towards ever greater mesh refinement levels [3,4]. With present CFD methods and computers, the highest achievable chord Reynolds number for fully resolved two-dimensional calculations of dynamic stall is Re = 100,000 [3], a factor of 40 from full scale. Direct simulations of unsteady leading edge separation were carried out [4] at a chord Reynolds number Re = 800,000. Achieving this result required a combination of extreme grid clustering and a very high-accuracy CFD algorithm. It is believed, based on [5], that full-scale simulation of dynamic stall is within reach in two dimensions, provided that the computational prediction tool incorporates both adaptive mesh refinement and high-accuracy algorithms. Achieving these two properties *simultaneously* and *efficiently* is one of the two key features of a method for accurate dynamic stall predictions; the other is good turbulence modeling.

In Phase I, NEAR reviewed the state-of-the-art in CFD methods, and spectral element technology was found to offer the most likely path to success. The Unstructured MacroCell (UMC) method is similar to spectral element schemes and has the potential of simultaneously addressing all of the above requirements.

The overall goal of this Phase II effort is to provide a CFD infrastructure suited to the prediction of dynamic stall at realistic Mach and Reynolds numbers. This goal will be achieved by developing a running two- and three-dimensional CFD code based on the unstructured macrocell concept, that uses high spatial accuracy and incorporates advanced turbulence and transition modeling capabilities.

WORK CARRIED OUT / RESULTS

Preliminary work on this contract began during the month of June. Since the task of developing a new CFD capability from the ground up is a considerable one, attention was paid to the foundations of the method, both from a technical and organizational point of view. An initial plan has been developed with regard to manpower and technical requirements. The aim is to articulate precisely a series of compartmentalized and well-defined research and/or coding tasks in order to make the best use of NEAR personnel. From a practical point of view, the project benefits additionally from the existence of an efficient software development infrastructure, namely: (1) CVS (distributed code revision system), (2) advanced Makefile capabilities, and (3) established error handling capabilities. Experience with all of these tools has been acquired under an earlier contract.[1] Together, they provide a software development

[1] U.S. Air Force Wright Laboratory contract number F33615-96-C-3613.

platform that will greatly facilitate the building of the UMC method.

The technical effort has focused thus far on the fundamental issues of high-accuracy spatial discretization versus metric discontinuities. One of the most challenging issues identified in the Phase I work [1] is that of preserving high-accuracy spatial discretization across macrocell boundaries. Since macrocell boundaries are omnipresent throughout the physical space being modeled, it is essential that high-accuracy be attained across boundaries if the flow solution is to remain globally of high accuracy.

The initial portion of this work concentrated on the evaluation of fluxes in the computational domain.[2] The assertions made in the proposal for this work were confirmed, namely that fluxes can be computed to fourth order accuracy on a triangular macrocell using a combination of values at points and shared first order derivatives at the boundary. However, the derived formulas pertained to the finite difference formulation. For conservation purposes, the finite volume formulation is preferable. Furthermore, the superiority of the finite volume formulation over finite differences is amplified in the case where the metrics are time dependent (i.e., in the presence of time-dependent or deformable grids). The review paper of Ref. [6] clarifies these important issues.

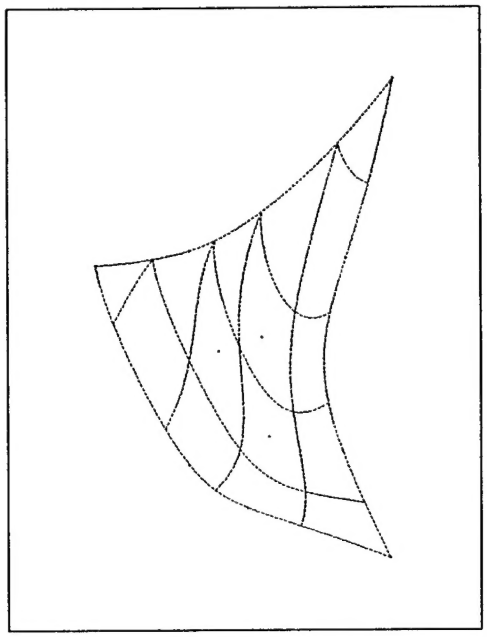

Fig. 1. TMC4 Element.

In the finite volume approach, the integral rate of increase of the solution at a grid point is calculated based on the cell boundary fluxes. Thus, the solution value associated with a grid point does not represent the solution at the grid point but, rather, the average of the solution over a volume surrounding that grid point. Consequently, the use of a high-accuracy (or high-order)[3] discretization formulae demands that consistent high-order metrics also be used. For example, the volumes need to be known with very high accuracy: there is no point using, say, a nine-point stencil to accurately determine the fluxes if the volume is only known to within five or ten percent! Simply stated, the difficulty stems from the fact that the volume edges can no longer be straight lines. Also, previous attempts at deriving higher-order metrics have been complicated by the fact that the volumes are *a priori* non-unique. Thus, a new approach must be considered.

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[2] (it is implicitly assumed that a mapping exists for each macrocell, which matches each point $\{x,y,z\}$ in the physical domain to a point $\{\xi,\eta,\zeta\}$ in the computational domain, typically with $\Delta\xi = \Delta\eta = \Delta\zeta = 1$)

[3] The difference between high-accuracy (optimized for wavelength) versus high-order (asymptotic convergence order) is only one of optimizing the underlying interpolation coefficients. For practical purposes, and for the purpose of the present argument, these terms can be used interchangeably since the width of the stencils is the same.

The approach that was experimented with here involves high-order macrocells. These high-order macrocells are curved cells in either two or three dimensions, which are generated using a set of control points. These control points define a unique metric transformation associated with that particular macrocell. In its most elementary form (i.e., linear), a triangular macrocell, for example, is defined by three control points which are the vertices of the triangle. The resulting mapping to computational space is a linear transformation. An example of nonlinear, high-order macrocell in two dimensions is the so-called TMC4 element, a triangular macrocell of quartic type (see Fig. 1). In the example of Fig. 1, the x and y coordinates of the physical space are mapped onto a uniform cartesian grid in computational space (not shown) using a special biquartic transformation. The transformation is made unique by the definition of 15 control points.

The advantages of a curved, high-order macrocell are twofold: (1) curved solid boundaries/surfaces can be accurately modeled (the grid points are *not* implicitly assumed to be connected to each other by straight line segments), and (2) the overall domain can be discretized using fewer macrocells, with each macrocell containing a larger number of microcells. In this manner, one can optimally take advantage of the speed, shock-capturing, and high-accuracy capabilities which have been developed for structured grids, while simultaneously reducing the computational effort associated with the (less efficient) unstructured portion of the calculation.

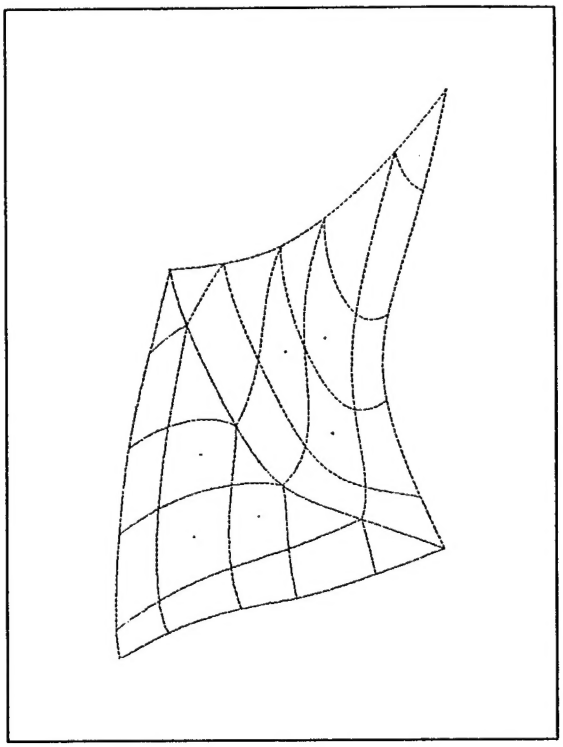

Fig. 2. Two Adjoining High-Order MacroCells.

Using the TMC4 element as an example, we have been able to prove the following:

(1) The volumes (defined in computational space by lines ξ = *const.* and η = *const.*) surrounding each control point can be computed analytically.

(2) If the inner (microcell) grid is laid out in a manner consistent with the metric transformation of the macrocell, then the individual microcell volumes can be computed analytically and are exact.

(3) The curved boundary of a macrocell matches exactly the boundary of the adjoining macrocell (Fig. 2).

While the high-order macrocell concept was developed primarily with the goal of computing the jacobian of the metric transformation (or, equivalently, the volumes) with an accuracy comparable to that

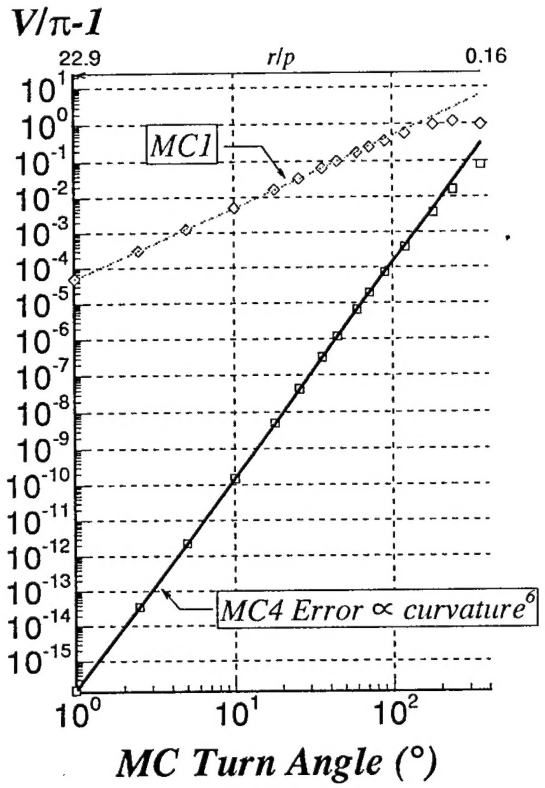

Fig. 3. Scaling of Volume Error as a Function of Curvature for Linear (MC1) and Quartic (MC4) MacroCell Elements.

of the discretization scheme used, it was incidently realized that (1) the volumes can actually be unique and exact (rather than simply high-order accurate) within a macrocell, and (2) the high-order macrocell has the added benefit of modeling spatial curvature reasonably well. To illustrate this point, consider the following exercise. Suppose we are interested in representing a circular disk using a finite number of macrocells. What is the number of macrocells needed, in order to compute the volume of the disk to a given level of accuracy? The error curves corresponding to the TMC4 high-order element and the TMC1 (i.e., triangular) element are shown in Fig. 3 as a function of the turning angle of the macrocell (a turning angle of 90° means one quarter of a circle, and so on (see Fig. 4)). It can be seen from Fig. 3 that the error using the quartic elements goes down with the sixth power of the curvature (as opposed to second power for the linear (conventional triangular) elements). This means, for instance, that the error incurred by covering the circle using 6 quartic elements (60° turning angle) is equivalent to the error incurred using 962 triangles. If the turning angle is 5° (72 quartic elements), approximately 1.7 million triangles are required in order to achieve the same level of accuracy.

Future Work. These encouraging preliminary results towards a precise and consistent definition of high-order finite volume metrics can be generalized to quadrilateral elements (in 2-D) and tetrahedra, pentahedra and hexahedra (in 3-D). Prior to doing so, however, it will be necessary to assess fully the consequences of this representation in terms of the flux computations. This is the foundation of the UMC partial differential equation solver (Task 1 of the Statement of Work) and, therefore, needs to be examined carefully and critically. Barring any unforeseen difficulties, it is anticipated that Task 1 should be completed on schedule.

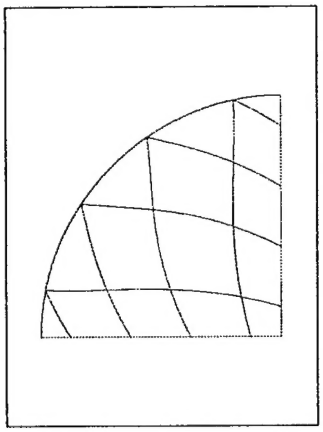

Fig. 4. Illustration of a Quartic MacroCell Having a 90° Turning Angle.

LIST OF PUBLICATIONS AND TECHNICAL REPORTS

No publications or technical reports for the current reporting period.

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